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Advancing Horticultural Crop Management: A Comprehensive Review Of Modern Methods And Techniques

Shubham Jain[1], Kokab Askari[2], Yogendra Pratap Singh[3], Abhilipsa Arya[4], Shikha Jain[5], Brajesh Kumar Mishra[6], Praveen Kumar Mishra[7], Guddu Kumar[8], Ramesh Chand[9], Devi Singh[10]
[1]Assistant Professor, Gyanveer University Sagar
[2]Assistant Professor, Maharishi Markandeshwar deemed to be University, Ambala
[3]Farm Manager, Krishi Vigyan Kendra, Katiya, Sitapur, Up 261145
[4]M.Sc. Ag Horti(Fruit Sc.) Sam Higginbotam University Of Agriculture, Technology & Sciences
[5]Assistant Professor, Gyanveer University Sagar
[6]Associate Professor Department Of Agriculture, Mm(Du), Mullana, Ambala, Haryana- 133207
[7]Subject Matter Specialist Horticulture, Krishi Vigyan Kendra Siddharth nagar, ANDUA&T Kumar ganj Ayodhya U.P.
[8]Ph.D. Scholar,Department Of Post Harvest Technology, Faculty Of Horticulture,Bidhan Chandra Krishi Viswavidyalaya, Mohanpur Nadia W.B 741252
[9]Assistant Professor Agriculture Engineering, Faculty of Agriculture, Maharishi Markandeshwar Deemed to be University Mullana Ambala Haryana -133207
[10]Professor Horticulture, Faculty of Agriculture, Maharishi Markandeshwar (Deemed to be) University, Mullana, Ambala Haryana - 133207

Abstract
Horticultural cultivation plays a crucial role in global food and nutrition security. This review explores recent advances and emerging trends in crop management, focusing on protected cultivation, precision agriculture, cultivar development, propagation innovations, micro-irrigation systems, nanotechnology applications, and integrated pest management. It highlights the potential of cutting-edge technologies like automation, robotics, artificial intelligence, and genetics to revolutionize horticulture. Key challenges such as sustainable intensification and the adaptation of plant systems to environmental changes are examined. The review emphasizes how the integration of advanced technologies and ecological approaches can lead to more productive, efficient, and climate-resilient horticultural systems. These innovations are essential for meeting the growing global demand for food while ensuring environmental sustainability.
Keywords: *Horticulture, Precision Agriculture, Protected Cultivation, Plant Breeding; Nanotechnology, Automation*

1. INTRODUCTION

Horticultural crop management plays a pivotal role in ensuring global food security, sustainable agriculture, and economic prosperity. In recent years, rapid advancements in technology such as robotics and artificial intelligence (AI), have transformed horticulture by optimizing various aspects of crop production, from planting to harvesting, improving both efficiency and output (Gupta and Gupta, 2024). Additionally, genome editing techniques like CRISPR-Cas9 and TALENs are unlocking new possibilities for crop improvement, allowing the development of disease-resistant and stress-tolerant varieties that enhance productivity and sustainability (Daniel et al., 2023 have revolutionized the field of horticulture, offering novel methods and techniquesto optimize crop production, improve resource efficiency, and mitigate environmental impacts.

This comprehensive review provides an overview of modern methods and techniques for advancing horticultural crop management, with a focus on precision agriculture, controlled environment cultivation, and innovative agronomic practices. Precision agriculture (PA) has emerged as a cornerstone of modern horticulture, leveraging advanced technologies such as Global Positioning System (GPS), Geographic Information System (GIS), and remote sensingto enable site-specific management of crops. Variable rate technology (VRT), automated machinery, and decision support systems (DSS) empower growers to optimize input use, monitor crop health, and make informed decisions in real-time (Sinha et al. 2023). PA facilitates precision planting, fertilization, irrigation, and pest management, resulting in increased yields, resource efficiency, and profitability. Controlled environment cultivation (CEC) encompasses a range of technologies and practices aimed at creating optimal growing conditions for horticultural crops. Greenhouses, polytunnels, and vertical farming systemsprovide protection from adverse weather, pests, and diseases while allowing for precise controlof temperature, humidity, and light intensity (Indurthi et al.

2024).Hydroponics, aeroponics, and aquaponics offer soilless cultivation methods, maximizing water and nutrient efficiency and enabling year-round production in urban environments. CEC systems integrate automation, sensors, and data analytics to optimize cropgrowth, quality, and marketability. Innovative agronomic practices contribute to sustainable horticultural crop management by promoting soil health, biodiversity, and ecosystem resilience. Conservation tillage, cover cropping, and integrated pest management (IPM) minimize soil erosion, nutrient runoff, and pesticide use while enhancing biological control and natural pollination. Organic and regenerative agriculture approaches prioritize environmental stewardship, emphasizing soil carbon sequestration, water conservation, and agroecosystem biodiversity. Agroforestry, intercropping, and crop rotation systems enhance ecosystem services, diversify farm income, and mitigate climate change impacts. Furthermore, advancements in biotechnology, genomics, and breeding techniques offer opportunities for developing improved horticultural crop varieties with enhanced traits such as disease resistance, abiotic stress tolerance, and nutritional quality. Emerging technologies such as geneediting, RNA interference, and marker-assisted selection accelerate the breeding process, enabling the development of resilient, high-yielding cultivars tailored to specific agroecological conditions and consumer preferences (Mishra., 2024).

The integration of modern methods and techniques is essential for advancing horticultural crop management in the 21st century. By embracing precision agriculture, controlled environment cultivation, and innovative agronomic practices, growers can enhance productivity, profitability, and sustainability while addressing the challenges of feeding a growing global population with limited natural resources. Continued research, education, and collaboration are needed to further optimize and disseminate these technologies for the benefit of horticultural stakeholders worldwide. Cultivation is one of the quickest developing and high-levels portions of horticulture around the world. It includes the development of naturalproducts, vegetables, ornamentals, ranch crops, fragrant restorative plants, and Flavors. With arising worldwide populace and expanding requests for better eating regimens, cultivation is pivotal for food and wholesome security (Mrabet et al. 2023). Green yields give fundamental nutrients, minerals, fibre, phytonutrients, and enemies of oxidants indispensable for human wellbeing. Worldwide plant creation in 2017 was assessed at 1.2 billion tons from north of 60 million hectares of developed land (Rathore, 2020). In any case, different difficulties stand up to the agriculture area in reasonably meeting raising creation needs. These incorporate declining arable land, environmental change influences, urbanization pressures, asset requirements like water shortage, rising information costs, postharvest misfortunes, and progressing to natural cultivating frameworks (Shah et al., 2024). Handling these complex, interlinkedissues requires tapping the capability of arising sciences, novel innovations and carefully empowered arrangements custom-made to green creation frameworks.

Ongoing many years have seen significant advances in protected cultivation, accuracy agribusiness, plant rearing developments, enhanced spread, crop improvement hereditary qualities, nanotechnology applications, miniature water system frameworks, and coordinated bug the board pertinent for cultivation (Reddy., 2024) This audit covers key advancements across these spaces, flow reception patterns, and the monstrous degree for continuous exploration and development. The groundbreaking prospects of arising advances like computerization, mechanical technology, man-made consciousness, and genomics are talked about. Challenges repressing innovation reception are analyzed, particularly for smallholder cultivators and creating locales. The audit gives experiences into how front line, biologically practical instruments and approaches can drive the eventual fate of cultivation.

2. Protected Cultivation and Climate Control

Protected cultivation of high-levels cultivation of crops under structures like nurseries, conceal nets, mulches and burrows has extended altogether as of late. It empowers positive microclimate conditions, assurance from biotic abiotic stresses, expanded developing periods,further developed yields and quality (Zheng & Xhu., 2023). Worldwide region under nursery development arrived at north of 1 million hectares in 2017, with significant extensions in China, India, Turkey and Mexico. Late advances in nursery innovation incorporate accuracy sensors for ongoing checking and mechanized environment control (Singh et al. 2023). PC controlled frameworks coordinate information from various sensors todirect warming, ventilation, moistness, lighting, water system, and CO2 supplementation for streamlining plant development (Indurthi et al. 2024). Advancements like evaporative cooling cushions, misting spouts, retractable rooftop covers, and intensity shades permit nurseries to keep up with appropriate conditions in assorted weather patterns (Garcia et al. 2019).

2.1 Advantages and Applications of Protected Cultivation:

Developments in nursery cladding include specific light dissemination, protection, infrared obstructing, hostile to condensate movies and UV assurance to make ideal microclimates. Plastics with further developed solidness, warm properties, light transmission qualities, and protection values are arising. Green-walls, aquaculture and hydroponics are being coordinated into nurseries for asset use productivity. Notwithstanding, high framework and working expenses of current nurseries present hindrances particularly for smallholder producers in creating districts (Michelson et al., 2023). Minimal expense protected cultivationchoices customized for neighbourhood conditions are fundamental. armadas show guarantee for computerized organic product reaping and picking. Notwithstanding, more extensive reception of these advancements faces hindrances like high forthright expenses, specialized intricacy, deficient rustic broadband foundation and cultivator mindfulness. Key open doors lie in creating arrangements custom fitted for smallholder ranches and tropical circumstances (Graham & Floering., 2024)

3. Precision Agriculture and Smart Systems

Precision farming means to empower information driven proficient asset the executives and improved efficiency. Late agricultural applications incorporate accuracy planting, designated showering, mechanized pruning gathering, independent robots, variable rate watersystem, drone checking, and choice emotionally supportive networks.

3.1 Precision Agriculture: Technologies and Benefits

GPS, GIS planning, remote sensor organizations, Enormous Information examination and the Web of Things are driving savvy accuracy arrangements (Reddy et al. 2023). Continuous yield screens utilizing phantom reflectance sensors on gatherers give intra field crop quality information to refine theexecutives rehearses. Remote soil dampness tests and plant sensors arranged through the cloud permit remote observing of water system needs and planning. Automated ethereal frameworks(UAS) furnished with multispectral cameras can rapidly check whole fields to analyse plant pressure and fluctuation for early intercession. Little robot armadas show guarantee formechanized natural product collecting and picking. Notwithstanding, more extensive receptionof these advancements faces hindrances like high forthright expenses, specialized intricacy, deficient rustic broadband foundation and cultivator mindfulness. Key open doors lie in creating arrangements custom-made for smallholder ranches and tropical circumstances (Chatterjee and Sharma, 2020).

4. Cultivar Development and Breeding Innovations

Cultivation crop variety is being extended through rearing progressions, presentation of intriguing germplasm, and further developed cultivars. Key targets incorporate better return potential, better wholesome quality, broadened time span of usability, resilience to biotic and abiotic stresses, and appropriateness for insignificant handling. Marker helped determination empowers fast reconciliation of attributes for bug infection obstruction, postharvest quality, and wholesome upgrade distinguished through hereditary planning review. Cross breed seeds and F1 assortments with mixture energy are speeding up yields of vegetables like tomatoes, peppers, melons, and Coles crops. Transformation rearing and polyploidy have created new cultivars like seedless triploid watermelons and tetraploid cabbage. New early-developing peach, apple, and citrus cultivars permit expansion of natural product creation into new scopesand environments (Basit & Lim et al. 2024).

Postharvest timeframe of realistic usability has been worked on through rearing Asianpears with upgraded ethylene and breath control. Presenting wild germplasm widens the hereditary variety pool for wanted characteristics. Significant cucurbit rearing advances incorporate infection safe cucumber, gynoecious melon half breeds, unpleasant free watermelon, and parthenocarpic summer squash. Saltiness lenient tomato cultivars have been reproduced utilizing wild family members local to waterfront environments. White strawberry assortments with improved flavour and time span of usability have been created. Genomics approaches like genome altering can speed up the rearing system from field to fork (Singh et al. 2023).

4.1 Propagation and Micropropagation

Ongoing proliferation progresses empower mass augmentation of excellent establishingmaterial to support cultivation efficiency. Further developed strategies for sexual / asexual spread and in vitro micropropagation guarantee more extensive accessibility of tip top cultivars.Aeroponics, aquaculture, fog chambers and hazing frameworks accomplish quick, high-throughput spread for vegetables, blossoms, products of the soil. Sand

aquaculture produced for lettuce engendering improves seed germination and seedling quality. Mechanized micropropagation frameworks grant all year creation of microbe free macroplants. Novel joining techniques encourage advancement of transgenic rootstocks in cucurbits for overseeingsoilborne sicknesses. Micrografting and tube uniting advances have empowered high productivity joining in tomatoes, eggplant, peppers, and watermelon even in little nurseries. Adjusted uniting cuts diminish work and expenses (Wang et al. 2024). More extensive utilization of value establishing material remaining parts obliged across agriculturalnations because of deficiencies underway framework, strategy backing and supply coordinatedfactors (Ramdas et al. 2023).

4.2 Nanotechnology Applications

Nanotechnology offers colossal expected in creating more brilliant frameworks for plant progression. Various applications incorporate nano-embodied composts and pesticides for controlled discharge, nanoparticles to improve crop development and stress resilience, nanochips for plant wellbeing observing, and nanocomposites for agricultural bundling. Silvernanoparticles consolidated in coatings, movies and bundling materials give longer and more extensive antimicrobial security during postharvest stockpiling and transport (Castro et al. 2019).

Nanotechnology in Horticulture: Innovations and Challenges

Nano sensors and nano biosensors empower fast ultrasensitive discovery of poisons, supplements, microbes, and plant wellbeing pointers for accuracy the executives. Quantum spot nano sensors recognize plant infections at femtomolar levels. Fluorescent nanoparticle labels and QR code nanoparticles empower following food provenance across supply chains. Challenges remain with respect to guideline, ecological effects, and businessinterpretation of nanotechnology for cultivation (Machado et al. 2023). Tending to well-being and security worries through thorough testing is indispensable.

4.2.1 Protected cultivation technologies

Protected cultivation technologies refer to a range of methods used in agriculture to create a controlled environment for plants, protecting them from adverse weather conditions, pests, and diseases. These technologies are often employed to extend the growing season, increase yields, and improve crop quality. Here are some common types of protected cultivation technologies:

1. **Greenhouses** - Encased structures covered with straightforward material to give controlled developing conditions shielded from outside vacillations. Empower all year new vegetable and bloom creation. compost application, and between line developing. Stay away from covers or holes. Greenhouses are structures made of transparentmaterials like glass or plastic that allow sunlight to enter while trapping heat inside. They provide a controlled environment for plants by regulating temperature, humidity, and ventilation. Greenhouses can range from small backyard structures to large commercial operations.
2. **Shade houses** - Basic roofed structures covered with conceal mesh to diminish daylight power for protected cultivation of shade-adoring harvests. Assist with relieving over thetop intensity. Shade houses are structures covered with shade cloth or mesh to reduce the intensity of sunlight reaching the plants. They are commonly used in hot climates toprotect sensitive crops from sunburn and heat stress while still allowing for adequate ventilation.
3. **Low tunnels** - Smaller than usual nursery structures made by bowing plastics or bars over beds and covering them with polyethylene films for brief assurance from climate. Give early season development.
4. **Polytunnels:** Polytunnels are similar to greenhouses but are typically covered with polyethylene plastic. They are less expensive to construct than traditional greenhouse and are commonly used by small-scale farmers and gardeners. Polytunnels offerprotection from weather elements and pests while allowing for natural light penetration.
5. **High Tunnels:** High tunnels, also known as hoop houses, are similar to polytunnelsbut are taller and arched, providing more headroom for taller crops. They are often used to extend the growing season in cooler climates and provide protection from frost, wind, and heavy rain.
6. **Mulching** - Covering soil with plastic sheets or natural materials to moderate dampness,diminish weeds, and make good microclimate. Advances plant development.
7. **Vertical Farming:** Vertical farming involves growing crops in vertically stacked layersor on vertical surfaces, often indoors or in controlled environments. This approach maximizes space utilization and allows for year-round cultivation in urban areas with limited land availability. Vertical farming systems typically incorporate artificial lighting, hydroponic or aeroponic growing methods, and climate control systems
8. **Controlled Environment Agriculture (CEA):** CEA encompasses various technologies and practices aimed at optimizing environmental factors such as light, temperature, humidity, and CO2 levels to

maximize plant growth and productivity. CEA systems often integrate advanced sensors, automation, and data analytics to monitor and controlgrowing conditions in real-time.

9. Aquaponics and Hydroponics: Aquaponics and hydroponics are soilless growing techniques that utilize water as the primary medium for delivering nutrients to plants. Inaquaponics, fish waste provides nutrients for plants, while in hydroponics, a nutrient solution is directly supplied to the plant roots. These methods are often used inconjunction with protected cultivation structures to optimize growing conditions and resource efficiency.

Overall, protected cultivation technologies offer innovative solutions to overcome environmental challenges and enhance agricultural productivity in diverse settings, ranging from small-scale urban gardens to large-scale commercial farms.

4.2.2 Precision agriculture technologies

Precision agriculture technologies, also known as precision farming or smart farming, involve the use of advanced technologies and data analytics to optimize various aspects of cropproduction and management. These technologies enable farmers to make more informed decisions, increase efficiency, and minimize inputs such as water, fertilizer, and pesticides while maximizing yields and environmental sustainability. Here are some key components of precision agriculture technologies:

a) Guidance systems - GPS-empowered work vehicle direction joined with GIS field maps for exact field tasks like splashing, compost application, and between linedeveloping. Stay away from covers or holes.

b) Variable rate application - GPS-directed application hardware changes input rates inlight of exact not entirely settled through remote detecting guides and soil tests. Streamlines asset use.

c) Crop sensors - Proximal optical sensors mounted on gear give continuous information on crop development and conditions for overseeing water system, supplements, and field changeability. Support early diagnostics.

d) Weather stations - Give restricted climate information like temperature, precipitation,mugginess, wind and so on to direct water system plans, anticipate illness episodes, andbacking ranch navigation.

e) Global Positioning System (GPS) and Geographic Information System (GIS): GPStechnology allows for accurate mapping and tracking of field boundaries, soil properties, and crop yields. GIS software integrates GPS data with other spatialinformation to create detailed maps for precise planning and decision-making.

f) Remote Sensing: Remote sensing technologies, including satellite imagery, drones (Unmanned Aerial Vehicles), and sensors, provide real-time data on crop health, nutrient levels, water stress, and pest infestations. This information helps farmers monitor field conditions and identify areas requiring attention or intervention.

g) Variable Rate Technology (VRT): VRT enables precise application of inputs such as fertilizers, pesticides, and irrigation water based on spatial variability within fields. Byadjusting application rates according to soil characteristics, crop requirements, and environmental conditions, farmers can optimize resource use and minimize waste.

h) Automated Machinery and Robotics: Automated machinery and robotics, includingautonomous tractors, harvesters, and drones, streamline field operations such as planting, spraying, and harvesting. These technologies improve efficiency, reduce labour costs, and enhance precision in task execution.

i) Precision Irrigation: Precision irrigation systems, such as drip irrigation and micro- sprinklers, deliver water directly to the root zone of crops based on soil moisture levels,weather forecasts, and crop water requirements. This minimizes water waste, improveswater-use efficiency, and mitigates soil erosion and salinity problems.

j) Crop Monitoring and Management Software: Crop monitoring and management software platforms collect, analyze, and visualize data from various sources to provide insights into crop performance, growth trends, and resource utilization. These platformsenable farmers to track inventory, plan planting schedules, monitor field conditions, and optimize agronomic practices in real-time.

k) Decision Support Systems (DSS): DSS use algorithms and predictive models to generate recommendations and prescriptions for optimizing crop management decisions. By integrating data on weather patterns, soil characteristics, crop growth stages, and market prices, DSS help farmers make informed choices to maximize profitability and sustainability.

l) Sensor Technologies: Sensor technologies, including soil moisture sensors, weather stations, and crop health sensors, collect data on environmental parameters and plant physiological indicators. These sensors provide valuable information for optimizing irrigation scheduling, detecting nutrient deficiencies, and identifying early signs of disease or pest infestations.

By integrating these precision agriculture technologies into their farming operations, growers can enhance productivity, profitability, and environmental stewardship while addressing the challenges of feeding a growing global population with limited natural resources.

5. MICRO IRRIGATION SYSTEMS

Miniature water system conveys water straight forwardly to the plant root zone or foliageutilizing effective techniques that limit water misfortunes. Trickle water system applies water through producers or drippers with stream rates up to 8 litters each hour. Subsurface dribble water system pipes set underground fundamentally vanishing misfortunes while empowering lessen fertigation. Miniature sprinkler and miniature splash water system convey exact water and supplement volumes to tree harvests and grape plantations (Mitcham et al. 2024) Above frameworks use influence or turning sprinkler heads with stream rates up to 200 litters each hour for uniform water circulation. A worldwide investigation tracked down normal water reserve funds of 33% with miniature water system reception, with yields improving in spite ofutilizing less water contrasted with traditional water system. Nonetheless, high establishment costs, support necessities, and restricted rancher mindfulness oblige more extensive reception,particularly in emerging nations (Naresh et al. 2023)

Institutional help for miniature water system through financed framework and rancher preparing will be critical. Key Creation Advances in Significant Organic product Harvests Huge developments in organic product creation, particularly for bananas, apples, grapes, strawberries and mangoes, are changing efficiency and quality. Banana reproducing programs are advancing with the guide of genomic choice to unequivocally distinguish illnesssafe and further developed quality assortments (Nyine et al. 2017). This permits designated crossing and determination even with complex polygenic characteristics. CRISPR quality altering has additionally been shown in bananas for fast presentation of gainful transformationslike Fusarium wither opposition, which causes enormous misfortunes worldwide. Postharvest medicines utilizing nitric oxide and 1-methyl cyclo propene (1-MCP) gas are being marketed to restrain ethylene creation and broaden green life and time span of usability of bananas (Zhuet al. 2019).

Apples High thickness plantations with minimal calculations presently rule apple development, empowered by trickle water system, automated pruning, and predominating rootstocks. Accuracy crop load the board through bloom/natural product diminishing advancesorganic product size and quality. Genomic helped reproducing has empowered advancement of biotic and abiotic stress strong apple assortments. Postharvest medicines with 1-MCP and dynamic controlled air (CA) stockpiling advancements assist with accomplishing low oxygenand high carbon dioxide conditions that lessen breath and related misfortunes for delayed capacity life (Javed et al. 2023)

6. Grapes

In grape plantations, computerized cultivating arrangements like automated airborne vehicles (UAVs) presently permit early yield gauging by dissecting overhang ascribes utilizingphantom symbolism. Deficiency water system plans are being upgraded utilizing soil and plantsensors to improve water efficiency and quality. Omic profiling approaches examining qualities, proteins and metabolites give experiences into grape advancement processes supporting quality improvement. Sulphur dioxide (SO_2) producing sheets are arising as synthetic free choices to check postharvest parasitic decays in table grapes during capacity. Strawberries Soilless aeroponic development incorporated with vertical multi-level development chambers and Drove lighting work with slow time of year strawberry creation. Plasticulture involving fumigation upgrades yields and organic product quality for fielddevelopment (Deseiger et al. 2022).

New cultivars with interminable blooming permit expanded reap length past customaryshort fruiting seasons. Mangoes High thickness mango plantations are making strides becauseof motorized pruning joined with reduced design and overshadowing rootstocks to expand efficiency. Postharvest plunge therapies utilizing boiling water or low portion illumination really control natural product flies as well as contagious rots during capacity. Time span of usability augmentation as long as three weeks has been accomplished utilizing Aloe vera gel- based eatable coatings advanced with rejuvenating oils. Progresses are being accounted for other natural product crops additionally like citrus, melons, peaches, cherries, pineapple and soon. Redoing innovation tool compartments in light of harvest science and homestead particularity is imperative for more extensive innovation reception. Postharvest Innovation Advances Postharvest misfortunes normal around half of produce in creating locales, underlining the requirement for financially savvy mechanical arrangements (Gustavsson et al.2011). Significant reasons for food misfortunes are mechanical harm, dampness misfortune, physiological weakening, microbial rot and

chilling injury during postharvest dealing with.

7. Emerging Technological Opportunities for Reducing Postharvest Losses Include

Consumable Coatings Slim eatable protein and polysaccharide-based coatings act as dampness hindrances holding water and surface. Normal biopolymers utilized incorporate starch, cellulose, chitosan, whey, zein, and gellan gum. Antimicrobial rejuvenating oils are in many cases consolidated as dynamic fixings. Coatings defer maturing and oxidation while upgrading microbiological security. Dynamic/Brilliant Bundling Consolidating oxygen safeguards, dampness control cushions, antimicrobial movies/particles and newness markers adds dynamic usefulness to bundling for kept up with quality (Joshy et al. 2024)

Dynamic bundling works by rummaging oxygen and dampness or delivering additives like sulphur dioxide, ethanol, plant removes relying upon produce breath. Savvy pointers signalmicrobial development or off-smell gathering for dynamic control. Nanotechnology Conveying antimicrobial metal/metal oxide nanoparticles (silver, zinc oxide, titanium dioxide)and nano-sensors increases wellbeing, following and observing. Nanoparticles act by upsettingcell layers, repressing catalysts and prompting responsive oxygen species in organisms. Remote nano-sensor networks empower fine-grained checking of produce geolocation, temperature, moistness and gas arrangement during capacity and transport for direction (Ranjitha et al. 2019).

8. Non-thermal Processing

Non-warm methodologies like bright (UV) radiation, ozone fumigation, ultrasonication and beat electric fields stay away from wholesome misfortune related with heat purification. UV focuses on the microbial DNA while ozone oxidizes cell parts. Ultrasound and electric heartbeats harm cell layers and modify compounds through mechanical or electromagnetic impacts instigating feasibility misfortune. Milder cycle systems guarantee security with low energy input. RFID Following Radio recurrence distinguishing proof (RFID) labels and remote sensor networks give thing level observing of travel conditions and empower cold chain the board (Regattieri et al. 2007). RFID labels connected to bundling offer contactless following and recording of sensor information like temperature. Constant perceivability of produce statushelps dynamic decision making for enhanced taking care of and stockpiling control.

Blockchain Stages Blockchain based circulated record stages offer inventory network straightforwardness and detectability by long-lasting timestamped recording of itemdevelopment, dissecting conditions and confirmation information (Tian et al. 2016). Decentralized sealed records increment trust through systemwide information dividing amongorganizations and customers. Blockchain likewise works with instalments, credibility claims and following start or manageability accreditations. Among postharvest developments, eatablecoatings, antimicrobial bundling, gentle handling innovations and nanotechnology arrangements straightforwardly upgrade produce timeframe of realistic usability other than quality confirmation (Ali et al. 2023). Production network perceivability innovations likeRFID and blockchain offer observing and smoothed out coordination benefits however require interoperability of information frameworks between partners. Putting resources into cold capacity framework, bundling houses, refrigerated transport and abilities advancement for besttaking care of practices remains similarly critical to shorten food misfortunes. Government approaches and guidelines likewise need to catalyse reception of arising science-based and computerized postharvest innovations. Eventually abridging financial misfortunes requires composed endeavours across the store network to hold nourishment and worth (Ashrafuzzaman., 2023).

9. Integrated Pest Management (IPM)

IPM plans to consolidate organic, social, physical and substance devices for comprehensive, environmental harvest assurance and manageable bug control. IPM procedures incorporate social practices like yield sterilization and revolution, organic control specialists, biopesticides, actual hindrances, pheromone traps, and safe cultivars. Nanotechnology additionally offers IPM arrangements through nano typified pesticides, nano biosensors for bother recognition, and antimicrobial nano-coatings. IPM reception brings different advantages including decreased pesticide use and buildups, avoidance of obstruction, preservation of normal adversaries, lower rancher openness to synthetics, and further developed sanitation (Ali at el. 2023). Notwithstanding, IPM faces reception hindrances with respect to specialized skill, forthright expenses, foundation accessibility, and strategy support. These should be tended to through multi-partner endeavours and more prominent preparation ofexpansion staff and ranchers (Zhu et al. 2019).

10.Future Prospects and Emerging Technologies

The Fourth Modern Unrest driven via robotization, man-made reasoning, mechanical technology, sensors, huge information investigation and the Web of Things is ready to changecultivation. Incorporation of these outstanding innovations can prompt brilliant, information driven, hyper-proficient agriculture frameworks. Independent robots are getting some decent momentum for work concentrated undertakings like reaping fragile foods grown from the ground salad greens. Apple-picking robots with fake vision have made more than 75% progressrates (Kale et al. 2024). Artificial intelligence models empower ongoing recognition of harvest illnesses and supplement lacks from elevated pictures for brief intercession. GPS-directed robots can perform super exact weeding to decrease agrochemical use (Kumar et al. 2023).

Blockchain innovation offers potential to follow crops from ranch to purchaser for improved discernibility and inventory network straightforwardness. Indoor vertical ranches furnished with Drove lighting, aqua-farming and robotization are growing new vegetable creation close to metropolitan focuses while limiting asset requests. CRISPR quality altering can quickly further develop characteristics for more significant returns, bug obstruction, naturalresistance, and sustenance (Younas et al. 2023). Utilizing such outstanding advances in a mindful, proof-based way will shape the eventual fate of cultivation. Nonetheless, innovation combination faces difficulties like high forthright expenses, absence of specialized information among ranchers, deficient rustic foundation in non-industrial nations, and concerns with respectto information protection, work influences, and impartial improvement (Anika et al. 2023). Comprehensive development approaches stressing smallholder consideration, limit building, and moderate organizations will be fundamental for capable reception. Fundamental to the innovation empowered cultivation future should be a rancher driven approach directed by maintainability (Freeman et al. 2022).

11.RESULTS

Worldwide agriculture is seeing major innovative advances supporting reasonable escalation across different sections from nurseries to protected cultivation to open-field production.

11.1 Propagation and Planting Material

Robotized micropropagation frameworks are arising to empower mass scale-up of tip topclones guaranteeing bug free and uniform establishing material. Novel cryopreservation strategies utilizing vitrification specialists work with long haul germplasm capacity in plant tissue banks. DNA fingerprinting validates parentage supporting rearing documentation and exclusive enrolments (Narida et al,. 2023)

11.2. Protected Cultivation

Nursery computerization through surrounding sensor organizations and choice emotionally supportive networks permits exact microclimate control for ideal development. Clever shade and warm screens save energy while establishing ideal conditions. SupplementalDrove lighting drives better returns and speedier harvests contrasted with customary practices.Aeroponics and other soilless frameworks empower slow time of year creation and better assetuse efficiencies (Shah et al. 2023).

11.3 Open Field Production

Motorized and automated arrangements are diminishing dependence on work for key field tasks like pruning, diminishing, collecting and reviewing natural product crops. Shade observing utilizing ethereal symbolism and proximal sensors advances data sources and gather operations. Shortfall water system improves water efficiency without yield misfortunes utilizing soil/plant criticism-based computerization. Novel biodegradable movies (biofilm) offer options in contrast to polyethylene mulch for weed control and dampness protection (Saini et al. 2024).

11.4 Vertical Farming

Indoor vertical homesteads utilizing IIoT, robotization and Drove lighting support all year yield close to metropolitan focuses. Staggered aquaculture, aeroponic or aquaponic food manufacturing plants empower accuracy agribusiness unconstrained by environment or soil factors. Postharvest misfortunes are limited attributable to safeguarded transport and capacity with lower food miles. Previous modern structures are being reused as eco-effective plant industrial facilities utilizing sustainable power and reused inputs (Benis et al. 2017).

11.5 Crop Protection

RNA obstruction and quality altering methodologies work with fast improvement of irritation/sickness safe assortments in products of the soil crops. Natural arrangements in viewof botanicals, microbials and semi synthetics check opposition issues contrasted with compound controls. Mechanized sprayers, pollinators and harvest exploring robots empower designated application limiting nontarget influences. Nano pesticides and nano embodied agrochemicals support adequacy at lower dosages than customary

definitions (Sahu & Kashew, 2023).

11.6 Post Harvest Management

Omic approaches reveal biomarkers for item quality aiding isolate produce and decideideal collect timing. Nonthermal handling utilizing UV, ozone, other arising advances guarantee wellbeing while at the same time saving nourishment. Dynamic bundling arrangements powerfully control inward air for newness maintenance. Radio recurrencedistinguishing proof (RFID) sensors and blockchain stages upgrade store network straightforwardness from homestead to purchasers. Atomic pharming produces high worth bioactive proteins and metabolites utilizing plants as bio factories (Galvez et al. 2018).

11.7 Key Production Advances

11.7.1 Fruit crops

Banana reproducing programs speed up involving genomic determination for qualities like Fusarium opposition and time span of usability. CRISPR quality altering targets agronomic attributes including protection against viral sicknesses. Novel postharvest medicines (nitric oxide, 1- MCP) expand green life by restraining ethylene creation. High thickness apple plantations are empowered by motorized pruning, trickle water system and overshadowing rootstocks to improve efficiency. Weather conditions station observed advantageous lighting further develops return blossom by up to 70 %. Controlled climate capacity and 1-MCP keep up with quality during cold capacity (Kobler et al. 2018).

Grapevine physiology models and proximal sensors guide advancement of watersystem, sustenance and covering design. Omic examination gives markers to quality characteristics and berry advancement. SO2 impregnated sheets are without compound optionsfor overseeing postharvest decays (Song et al. 2015).

Aeroponics, crossover lighting advances and interminable blooming hereditary qualities broaden strawberry creation past seasons. High thickness mango plantations amplifyyields through minimal design, motorized pruning and predominating rootstocks. Low portion light, natural balms and biocontrol successfully oversee postharvest anthracnose, stem end decay and organic product flies. Comparative creation and postharvest progresses are being carried out across agriculture items to improve efficiency and worth (Crisan et al. 2023).

11.7.2 Protected cultivation

Nursery crop yields are 1.5 to twice higher than open-field development by permittingpositive temperature, dampness and light circumstances. Semi consistent creation empowers out-offseason accessibility and solid stockpile chains. Netherlands has spearheaded ultra innovative glasshouse offices accomplishing efficiency north of 40 kg/m^2 yearly for tomatoesutilizing supplemental LEDs and aqua-farming (Graamans et al. 2018).

Conceal houses, polyhouses and net houses are making progress as minimal expense safeguarded structures across Asian and African nations. Almost 10,000 hectares are added yearly under polyhouse development in India with showed benefits in capsicum, cucumber, rose and carnation (Gautam et al. 2024).

Environment gambles are driving vertical extensions like staggered indoor offices for raising nursery saplings. Housetop nursery establishments and holder cultivating models are becoming suitable metropolitan creation options. Reception of sustainable power advancements can relieve difficulties connected with lighting and cooling costs over the long haul (Ntinas et al. 2017).

11.7.3 Hydroponics and Aeroponics

Soilless development strategies including tank-farming and aeroponics empower more prominent command over the root zone climate for further developed efficiency and quality. They significantly diminish water and supplement necessities contrasted with customary strategies since arrangements are recycled without spillage or overflow misfortunes. Aeroponics joined with indoor vertical cultivating gives cost advantage over costly fake lighting in single layer nurseries (Graamans et al. 2017).

Aero Farms claims north of 900 times higher result for each hectare for mixed greens developed involving reused textures in stacked levels under Drove lighting. Focal checking permits distant oversight without consistent human presence. Nonetheless, reinforcement power and specialized abilities are indispensable to stay away from framework crashes (Khosaet al. 2018).

Interests in Research and development can improve effectiveness, grow crop decisions and drive modularization for more extensive reception past cutting edge nations. Great strategy support for foundation, specialized preparing and input accessibility will demonstrate conclusive for controlled climate horticulture methods (Kalantari et al. 2017).

11.7.4 Robotics and Automation

The goal of agricultural robotics is to reduce the high costs of manual labour while simultaneously increasing farm productivity. With over 90% accuracy, vision-guided robotic

arms selectively harvest ripe strawberries and apples. Reaching cost targets below $10,000 forfarm-scale viability remains a challenge. Improving delicately treatment of delicate produce likewise needs continuous development. Automated Pasto Pod spot sprayers that matched theshape of the canopy enabled pesticide reductions of 64-87 percent in orchard sprayingapplications. Comparably designated compost conveyance to grapevine root zones expanded supplement take-up effectiveness up to 85% contrasted with broadcast techniques (Gongal et al. 2015). Variable rate water system guarantees significant water reserve funds however includes high introductory machine costs by and by. With internet-connected technologies accounting for more than half of commercial production of grapes, strawberries, and tomatoes,Japan leads the way in horticulture automation. Self-driving work vehicles, weeding robots andorganic product picking machines will disturb open field creation as advancements emerge intobusiness arrangements over the course of the following ten years (Shah et al. 2023).

The use of 5G mobile networks would make widescale coordination fundamental for acknowledging independent homestead ideas. India provides a Drones or unmanned aerial vehicles (UAVs) for agricultural purposes have a $500 million market opportunity. across cropwellbeing checking, showering and land review applications by 2025. Multispectral camera- equipped unmanned aerial vehicles (UAVs) measure yield estimates or vegetation indices thatindicate irrigation requirements weeks before harvest. However, adoption is currently hampered by beyond line of sight restrictions. Although it lacks plot-level details, satellite remote sensing offers cost-effective alternatives for regional analytics. Developments in sunlight based environmentally friendly power gathering, battery capacity arrangements and material designing mean falling costs directions for computerization advancement. Over small,marginal holdings outside of controlled research station environments, a larger deployment would demonstrate reliability (Shamshiri et al. 2018).

11.7.5 Hydroponic Fodder Production

Aquaculture grub frameworks work with decentralized, land free animals feed creation while utilizing multiple times less water than field developed grains. Seven-day sprouted barleyor maize has over 20% protein and a lot of antioxidants, whereas mature hay only has 12% protein. Cows took care of with such green grain give 12-15% higher milk yields contrasted with dry feed alone. India has seen an increase in the number of small hydroponic fodder businesses that supply dairy farmers with nutritious animal feed made from recycled containers. Micro irrigation systems that are affordable circulate nutrient solutions, scattering seedsthat are kept in trays until they sprout. Driven lighting combination empowers all year steady result (Vijayakumar et al. 2018). These soilless, highly productive feed systems offer climate-conscious, ethical alternatives that lessen the demand on land and water resources. More extensive reception depends on showing long haul monetary feasibility and nourishing qualityto ranchers other than underlying enhancements dealing with seepage reusing. High-tech infrastructure for secure cultivation, such as polyhouses and net houses equipped with micro- irrigation, is funded by government programs like the Rashtriya Krishi Vikas Yojana. Confidential area players are entering contract cultivating organizations while utilizing advanced stages to associate nearby harvest makers to metropolitan purchasers (Gebeyew et al. 2021).

11.7.6 Nutrient Use Efficiency

Adjusted treatment satisfying yield needs is imperative to raise efficiency, ranch wages and natural supportability. Site explicit supplement the executives (SSNM) tailor's proposals to spatial soil changeability and yield potential. Rice yields expanded 10-15% while saving 20-25 kg/ha urea involving SSNM procedures across towns in India. Developing dependence on imports surpassing half of utilization underlines critical upgrades required in compost use productivity for India's food security desires. Almost half of applied nitrogen is lost by means of draining, denitrification and volatilization causing contamination. Urea profoundarrangement and neem/polymer covered manures showing diminished misfortunes need strategy impetuses to extend producing. Prescriptions based on soil tests, leaf colour charts thatindicate changes midway through the season, and decision tools that make use of infrared spectroscopy are all ways to improve nutrient recovery (Majumdar et al. 2019). Ongoing nitrogen observing permits variable rate conveyance matching yield requests across creation scenes. Organizations along Sustainable nutrient stewardship programs can be promoted by theagrifood value chain. Government is advancing soil wellbeing cards benchmarking ranch levelstatus while sponsoring otherwise out of reach for smallholder farmers are micronutrients. Models for judicious use of nutrients and pesticides include production clusters, contract farming models, and collective input procurement through farmer producer organizations (Watson et al. 2018).

11.7.7 Climate Resilience

In order to maintain farmer incomes and productivity in the face of climate change's exacerbation of weather variability, it has become crucial to develop resilient varieties. Speedreproducing conventions speed up age turnover utilizing expanded photoperiods and controlleddevelopment chambers. Marker helped repetitive determination permits exact stacking of intricate dry season resilience qualities connected with water use proficiency, root design and osmotic changes. CRISPR-Cas9 empowers designated altering of environment strength qualities like those controlling stomatal conductance, chloroplastic capabilities and senescenceelements. When compared to transgenic crops, genome-editing crops typically face lower regulatory barriers for release. Climate smart villages that demonstrate integrated adaptation strategies provide institutional innovation that bridges interventions in technology, agriculture,finance, and policy. Hyperlocal advisories are aided by crowdsourced weather data. Climate vulnerability is addressed by index insurance, price guarantees, warehousing integration, crop diversification, and other methods. Mainstreaming orientation comprehensive practices, socialassurance plans and environment proficiency programs guarantees weak networks have risk adapting limits. Farm livelihoods are improved by improving rural infrastructure like roads, electricity, and resilience to extreme events (Doloi., 2024).

12 DISCUSSION

The outcomes uncover groundbreaking yet early advancements across nurseries, safeguarded zones and open field agriculture creation frameworks. Innovation implantation with science and biology standards can catalyse manageable additions in efficiency, benefit and natural execution all the while. Engendering material quality and wellbeing confirmation structure the beginning stage for life span and efficiency pursuits (Kargas et al. 2015). Aeroponics, aquaculture and vertical ranches make conceivable beforehand impossible editingchoices in modern spaces.

Robotization and astute choice devices guide unequivocally custom fitted harvest the executives for advancing both quality and yields. Consolidating the furthest down the line advances will demonstrate fundamental for makers to hold their strategic advantage. Government and industry associations ought to channel more prominent Research and development speculations for logical requirements while adjusting tradeoffs. Moderate strategies and administrative structures should stay up with mechanical change to tackle amazing open doors mindfully while relieving gambles. Quality altering is a flexible rearing strategy however off-target impacts and biological issues like quality stream warrant progressing evaluation (Peng et al. 2017).

Most nations actually need upgraded lucidity among more established and current rearingtechniques. Nano pesticides, microbial biostimulants and engineered science additionally require proof-based oversight and life cycle assessments. Worldwide harmonization of guidelines would help worldwide dispersion by adjusting irregularities. Genuine problematic development requires rethinking whole worth chains as opposed to steady increments (Yadaet al. 2001). Blockchain joining in Agrifood supply binds upgrades start to finish straightforwardness helping assorted partners. Round models limiting waste by means of asset recuperation and reuse are acquiring conspicuousness. Previous brownfield locales are being changed over into vertical foundation for eco-proficient all year creation. Result based plans ofaction warrants pilot testing to evaluate practicality. Environment savvy advancements ought to be focused on given the existential dangers presented by climate limits, water shortage among different difficulties (Uekotter et al. 2024).

Satellite directed warnings on dry season or flood gambles permit early mediations to moderate efficiency misfortunes. Genome altered environment tough cultivars offer enduring arrangements yet may confront exchange obstructions lacking global agreement on guideline.Reinforcing rustic foundations and social insurance are indispensable to make cultivating networks strong (Khosa et al. 2018).

13 CONCLUSION

This review highlights significant advances and emerging opportunities across various aspects of horticultural production and management. Protected cultivation, precision agriculture, improved cultivars, advancements in propagation, and micro-irrigation systems offers sustainable pathways to enhance productivity, quality, resource efficiency, and farm income. Integrated Pest Management (IPM) and nanotechnology also promote eco-friendly cultivation. However, addressing key gaps is essential to fully unlock the potential of innovation-driven sustainable horticulture. Developing tailored solutions for smallholder systems in diverse climates is critical. Empowering youth and women through inclusive policies and collaborative frameworks can accelerate technology adoption. Ongoing research and development must align new tools with agroecological goals to ensure sustainable agricultural ecosystems. Horticulture's future

lies in inclusivity, environmental integrity, climate resilience, and shared prosperity. Future research should focus on integrating advanced technologies with localized practices to create scalable, sustainable models for global food security and environmental balance.

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